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On the origin of TeV radiation of SN 1006

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Abstract. We discuss the link between the nonthermal X-radiation and TeV γ -ray emission from SN 1006, and study the capabilities of both electronic and nucleonic models for explanation of the TeV flux observed from the northeast rim of SN 1006. We show that the interpretation of the TeV radiation by the inverse Compton scattering of electrons on 2.7 K cosmic microwave background radiation is possible, however due to the escape of high energy electrons, the γ -ray emission should be significantly contributed not only from the rim, but also from the inner parts of the remnant. This implies an angular size of the TeV γ -ray emission larger than the size of the nonthermal X-radiation. In this scenario the magnetic field in the rim should not exceed $10 \mu\text{G}$. Then, in order to allow acceleration of particles well beyond 10 TeV the shock speed should be high, $\geq 3000 \text{ km/s}$. The latter condition gives preference to a large distance to the source, $d \simeq 2 \text{ kpc}$ or so which is in the limits of distances currently discussed in the literature. On the other hand, a larger magnetic field of order $100 \mu\text{G}$ and smaller shock speeds (and therefore a small distance to the source of about 1 kpc) are not excluded. In that case the observed TeV radiation can be explained by shock accelerated protons in the rim through production and subsequent decay of π^0 -mesons. Contrary to IC radiation, the π -decay γ -ray source coincides essentially with the rim, and therefore it could be recognized by a relatively compact angular width. Both the electronic and nucleonic models require high efficiency of particle acceleration close to the Bohm limit, and large total energy in accelerated particles at the level of respectively 1% and 10% of the kinetic energy of explosion of SN 1006. We discuss observational possibilities to distinguish between electronic and nucleonic origins of γ -radiation.

Key words: radiation mechanisms: non-thermal – supernovae: individual: SN 1006 – gamma rays – X-rays

1. Introduction

The flux of cosmic rays is described by a smooth single power-law spectrum which extends up to the so-called ‘knee’ around 10^{15} eV . This can be interpreted as an evidence that the bulk of galactic cosmic rays is produced by a single source population. Since the early 60’s the supernova remnants (SNRs) are believed to be the most probable sites of acceleration of galactic cosmic rays (see e.g. Ginzburg & Syrovatskii 1964), the basic argument being that the galactic Supernovae (SNe), and the resulting supernova remnants (SNRs) are almost the only known potential sources with available (kinetic) energy needed to provide the observed luminosity of the Galaxy in cosmic rays, $L_{\text{CR}} \geq 10^{40} \text{ erg/s}$. Moreover, it has been shown (see e.g. Drury 1983, Blandford & Eichler 1987, Berezhko & Krymski 1988, Jones & Ellison 1991) that a viable mechanism – diffusive shock acceleration – can effectively operate in relatively young SNRs accelerating particles to 100 TeV (Lagage & Cesarsky 1983) or perhaps to higher energies (Völk & Biermann 1988). The strong shocks in SNRs provide not only very effective, 10 per cent or more, conversion of the total SN explosion energy into the accelerated particles but also can naturally explain hard ($\propto E^{-\Gamma}$ with $\Gamma \sim 2.0-2.1$) source spectrum which follows from the standard ‘leaky box’ propagation model of galactic cosmic rays (see e.g. Gaisser 1990).

The nonthermal (synchrotron) radio emission observed from shell-type SNRs is an unambiguous indicator of acceleration of GeV electrons there. Possible association of some of the γ -ray ‘hot spots’ detected by COS B (Bhat et al. 1985; Pollock 1985; Wolfendale & Zhang 1994) and EGRET (Sturmer & Dermer 1994; Esposito et al. 1996) with galactic SNRs could be another evidence for acceleration of electrons and possibly also protons in SNRs (Blandford & Cowie 1982, Sturmer et al. 1997; Gaisser et al. 1998; Baring et al. 1999). However these observations concern only the low energy, typically $E \leq 10 \text{ GeV}$ particles, therefore they cannot yet conclusively argue in favor of SNRs as suppliers of the whole spectrum of galactic cosmic rays. An unbiased proof of this hypothesis can be provided only by detection of TeV γ -radiation produced

at interactions of accelerated protons and nuclei with ambient gas through production and subsequent decay of π^0 -mesons (Drury et al. 1994; Naito & Takahara 1994) and/or by accelerated electrons upscattering the 2.7 K MBR (Mastichiadis 1996). Therefore it is difficult to overestimate the significance of the discovery of TeV radiation from the historical supernova SN 1006 reported by the CANGAROO collaboration (Tanimori et al. 1998).

Actually the first, although rather circumstantial evidence for the presence of ultrarelativistic particles in SN 1006 was found two decades ago by means of X-ray observations. It was suggested that the power-law X-ray spectrum of SN 1006 observed by the Einstein (Becker et al. 1980) and EXOSAT (Jones & Pye 1989) satellites could be explained by synchrotron radiation of electrons accelerated in the SNR shell (Reynolds & Chevalier 1981, Amosov et al. 1994). The recent detection of a spatially resolved power-law component of hard X-radiation from the edges of the remnant of SN 1006 by ASCA (Koyama et al. 1995) and ROSAT (Willingale et al. 1996) strongly supports the synchrotron origin of the radiation that implies acceleration of electrons to energies ~ 100 TeV. It should be noted that a featureless, power-law spectrum of X-radiation could be produced by a plasma with multi-temperature structure (Hamilton et al. 1983), or by a heavy-element-dominated plasma with possible deviation of the electron distribution from the standard Maxwellian spectrum (Laming 1998). Therefore the very fact of detection of a power-law component of X-radiation does not yet automatically imply a nonthermal origin of the radiation. However in the case of SN 1006 the thermal interpretation of the continuous X-radiation faces serious difficulties, and the preference therefore is given to the nonthermal synchrotron hypothesis (Koyama et al. 1995; Laming 1998).

Motivated by this fact, several theorists (Pohl 1996; Mastichiadis & de Jager 1996; Yoshida & Yanagita 1997) predicted detectable fluxes of inverse Compton (IC) TeV emission. Remarkably, very soon this object has been detected as a TeV emitter (Tanimori et al. 1998). Both the reported flux and the spatial position of the TeV source centered on the NE rim are close to the predictions. This circumstance strengthened the belief in the electronic origin of TeV radiation. The π^0 -decay contribution to the observed flux is widely considered as less important.

However, given the fact that SN 1006 is the only shell-type SNR reported as TeV γ -ray source, a careful examination of different scenarios of γ -ray production is obviously needed prior to exclude the nucleonic origin of the observed TeV radiation (Aharonian 1999). In particular, the contribution of the π^0 -decay γ -rays could be enhanced to the level of the observed fluxes if we assume a relatively small distance to the source of about $\simeq 1$ kpc (Willingale et al. 1996), as well as take into account a significant compression of gas in the NE rim by the shock. It is important that this scenario does not limit the magnetic field in the acceleration region to values comparable with the

interstellar B-field as required by the IC models of the observed TeV radiation. The magnetic field in the rim could be then as high as $B \sim 100 \mu\text{G}$ which is favorable for acceleration of particles up to $\gg 10$ TeV, taking into account the young age of SN 1006. Obviously in both scenarios the nonthermal X-ray emission observed from the NE rim is explained by synchrotron radiation of directly accelerated electrons.

The current data do not allow us to give preference to the electronic or nucleonic origin of the observed TeV radiation. In this paper we study in detail the spectral and spatial characteristics of the IC and π^0 -decay γ -rays. In particular we show that while the size of π^0 -decay γ -ray emission is expected to be of the size of the rim, the size of the inverse Compton TeV source should be significantly larger because of inevitable escape of very high energy electrons from the acceleration region, and their subsequent upscattering of the 2.7 K MBR outside of the rim.

2. Inverse Compton versus π^0 -decay γ -rays

For a “standard” injection spectrum of shock-accelerated particles (protons and electrons) in a SNR,

$$Q(E) \propto E^{-\Gamma} \exp(-E/E_0), \quad (1)$$

with $\Gamma \approx 2$ and $E_0 \approx 100$ TeV, the flux of π^0 -decay γ -rays at $E \leq 0.05E_0$,

$$F(> E) \approx 10^{-11} A(E/1 \text{ TeV})^{-1} \text{ ph/cm}^2\text{s}, \quad (2)$$

is determined by a simple scaling parameter,

$$A = (W_{\text{CR}}/10^{50} \text{ erg}) (n/1 \text{ cm}^{-3}) (d/1 \text{ kpc})^{-2}. \quad (3)$$

Here W_{CR} is the total energy in relativistic protons, n is the ambient gas density, and d is the distance to the source.

The peak luminosity of γ -rays is reached at the early Sedov phase (Berezhko & Völk 1997), i.e. typically $10^3 - 10^4$ years after the SN explosion. At this stage the radius of the shell exceeds several parsecs. This results in a typical angular size of relatively close ($d \leq 1$ kpc) SNRs of about 1° . The apparent conflict, from the point of view of source detectability, between the angular size ($\phi \propto 1/d$) and the γ -ray flux ($F_\gamma \propto 1/d^2$) significantly limits the number of SNRs which could be detected by the current most sensitive imaging atmospheric Cherenkov telescopes (IACT), to the range of $A \geq 0.1$. Future large stereoscopic IACT arrays will extend this limit down to $A \sim 0.01$ (Aharonian & Akerlof 1997).

When extracting information about the accelerated protons one has to subtract a possible non-negligible “contamination” caused by parallelly accelerated electrons that upscatter the photons of 2.7 K MBR (which is the dominant target photon field for production of TeV photons in most of SNRs; see e.g. Gaisser et al. 1998) up to

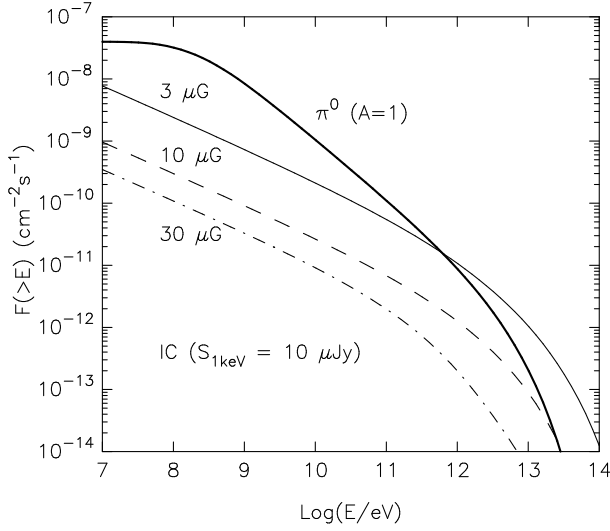


Fig. 1. The integral fluxes of π^0 -decay (heavy solid line) and IC (thin lines) γ -rays from a 10^3 year old SNR. The π^0 decay γ -rays are calculated for the scaling parameter $A = 1$. The IC γ -ray fluxes are calculated for 3 different values of the magnetic field $B = 3$ (solid curve), 10 (dashed curve), and $30 \mu\text{G}$ (dot-dashed curve), assuming the electrons produce the same flux of synchrotron radiation $S_\nu = 10 \mu\text{Jy}$. For both the protons and electrons we assume the same injection spectrum given in the form of Eq.(1) with $\Gamma = 2$ and $E_0 = 100 \text{ TeV}$.

γ -ray energies. For production of IC γ -rays of TeV energies multi-TeV electrons are needed. The same electrons produce also synchrotron UV/X-ray radiation. The typical energies E_γ and E_X of the IC and synchrotron photons produced by an electron are related as (see e.g. Aharonian et al. 1997)¹

$$E_\gamma \simeq 1.5(E_X/0.1 \text{ keV}) (B/10 \mu\text{G})^{-1} \text{ TeV}. \quad (4)$$

The ratio of the synchrotron and IC fluxes $f_E \equiv E^2 F(E) = \nu S_\nu$ at these energies does not practically depend on the shape of the spectrum of parent relativistic electrons, but strongly depends on the magnetic field:

$$\frac{f_{\text{IC}}(E_\gamma)}{f_{\text{sy}}(E_X)} \simeq 0.1 (B/10 \mu\text{G})^{-2} \quad (5)$$

For the X-ray spectrum with photon index $\alpha_X \sim 2$ the energy flux f_X is almost energy-independent. Therefore f_X at a typical energy of 1 keV could serve as a good indicator for the IC γ -ray fluxes expected at TeV energies, although for magnetic fields $B \leq 100 \mu\text{G}$ the energy of synchrotron photons relevant (produced by the same parent electrons) to $\sim 1 \text{ TeV}$ γ -rays is in the soft X-ray domain (see Eq. 4).

The contribution of π^0 -decay γ -rays dominates over the contribution of the IC component when

$$A \geq 0.1 (S_{1\text{keV}}/10 \mu\text{Jy}) (B/10 \mu\text{G})^{-2}, \quad (6)$$

¹ Note that this relation neglects the Klein-Nishina effect which becomes important at energies $E_\gamma \geq 10 \text{ TeV}$.

where $S_{1\text{keV}}$ is the flux of nonthermal synchrotron radiation at 1 keV normalized to $10 \mu\text{Jy}$ (the corresponding energy flux $f_X \approx 2.4 \times 10^{-11} \text{ erg/cm}^2\text{s}$). Note that $S_{1\text{keV}} = 10 \mu\text{Jy}$ is a typical level of nonthermal X-ray fluxes reported recently from four shell-type SNRs – SN 1006 (Koyama et al. 1995), Cas A (Allen et al. 1997), IC 443 (Keohane et al. 1997) and RXJ1713.7-3946 (Koyama et al. 1997).

In Fig. 1 we present integral fluxes of π^0 -decay and inverse Compton γ -rays from a SNR of age 10^3 yr. The π^0 -decay γ -ray flux corresponds to the scaling parameter $A = 1$. The IC fluxes are calculated by normalizing the synchrotron X-ray fluxes to $S_{1\text{keV}} = 10 \mu\text{Jy}$ for ambient B-fields $3 \mu\text{G}$, $10 \mu\text{G}$, and $30 \mu\text{G}$. For both electrons and protons we assume continuous acceleration during 10^3 years with a time-independent source spectrum taken in the form of Eq.(1) with $\Gamma = 2$ and $E_0 = 100 \text{ TeV}$. Note that for the normalizations used, the results presented in Fig. 1 only slightly depend on the source age, unless it is larger than the radiative cooling time of multi-TeV electrons, $t_{\text{rad}} \approx 10^4 (B/10 \mu\text{G})^{-2} (E_e/10 \text{ TeV})^{-1} \text{ yr}$.

3. Synchrotron and IC components of nonthermal radiation of SN 1006

The bulk ($\simeq 75\%$) of the nonthermal X-ray component of SN 1006 is contributed by the northeast (NE) and the southwest (SW) rims (Koyama et al. 1995, Willingale et al. 1996). The observations of SN 1006 by the CANGAROO collaboration (Tanimori et al. 1998) have revealed TeV radiation from the NE rim, but only an upper limit from the SW rim was reported. Therefore in this paper the nonthermal radiation of only NE rim is discussed.

For the spectral characteristics of the nonthermal X-ray emission of NE rim we follow the procedure used by Mastichiadis & de Jager (1996). Namely we assume that the X-ray spectrum below 1.5 keV is described by a power-law with mean photon index $\alpha_x \simeq 2.2$ as it follows from the combined Einstein/EXOSAT/ROSAT data. At higher energies up to 8 keV the spectrum reported by ASCA from NE+SW rims is significantly steeper, with a power-law photon index $\alpha_x \simeq 3$. For the estimate of the absolute X-ray flux from NE rim we take into account that $\simeq 60\%$ of the total emission of NE and SW rims is contributed by NE rim, as it follows from the respective count rates of ROSAT (see Willingale et al. 1996). The resulting range of the X-ray fluxes observed from the NE rim in the range from 0.1 keV to 8 keV is shown in Fig. 2.

The radio emission of SN 1006 has a power-law spectrum with an index $\alpha_r \simeq 0.57$ and intensity 30.8 Jy at 408 MHz (Stephenson et al. 1977). In Fig. 2 one half of this flux is taken because the observed total radio flux is equally contributed from the northeast and southwest directions (see e.g. Reynolds & Gilmore 1986).

In Fig. 2 we show also the range of TeV γ -ray fluxes observed by CANGAROO from the direction of NE rim

of SN 1006 at energies above 1.7 TeV (Tanimori et al. 1998), as well as the EGRET flux upper limit from SN 1006 (Mori 1997).

3.1. One zone model

In this section we assume that synchrotron and IC γ -rays are produced by relativistic electrons confined in a spatially homogeneous rim. In this simplified case the IC fluxes shown in Fig 1 could serve as first approximation estimates for the expected TeV γ -radiation. However, more reliable predictions of γ -ray fluxes require a careful derivation of the spectrum of ≥ 10 TeV electrons which is controlled by the spectrum of synchrotron X-rays.

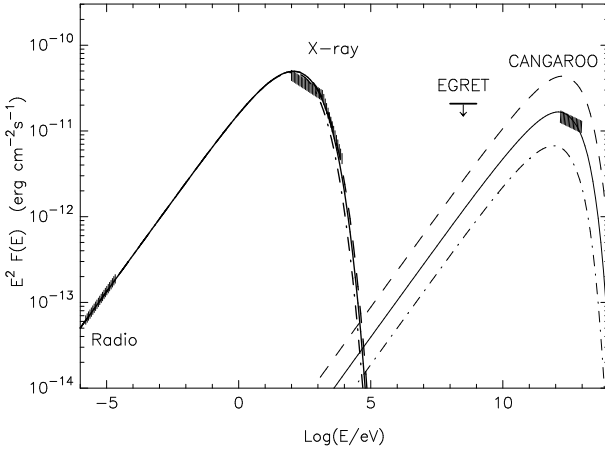


Fig. 2. The synchrotron (heavy lines) and IC (thin lines) fluxes calculated for the homogeneous source without escape of accelerated particles (one-zone model). Power-law injection spectrum of electrons with $\Gamma_e = 2.15$ is assumed in order to fit the radio data. The maximum energy E_0 is determined from the condition given by Eq.(9) for 3 different values of the magnetic field: $B = 3 \mu\text{G}$ (dashed line), $5 \mu\text{G}$ (solid line), and $8 \mu\text{G}$ (dot-dashed line).

In the synchrotron-inverse Compton models the spectral fit to the X-ray flux is crucial because the fluxes are produced by electrons in the region of the exponential cutoff E_0 between 10 and 100 TeV. The spectral index Γ of accelerated electrons is derived from the radio data, $\Gamma = 1 + 2\alpha_r \simeq 2.15$. Information about E_0 in Eq. (1) is contained in the X-ray spectrum. In particular case of negligible energy losses, the spectrum of electrons $N(E_e)$ repeats the injection spectrum, $N(E_e) \propto Q(E_e)$, therefore in the δ -functional approximation for the synchrotron emissivity, the X-ray spectrum can be presented in a simple form (see e.g. Yoshida & Yanagita 1997, Reynolds 1998)

$$F(E) \propto E^{-(\Gamma+1)/2} \exp[-(E/E_m)^{1/2}], \quad (7)$$

where

$$E_m \simeq 0.29 h \nu_c \simeq 0.02 (B/10 \mu\text{G}) (E_0/10 \text{ TeV})^2 \text{ keV} \quad (8)$$

is the mean energy of synchrotron photons produced by an electron of energy E_0 (ν_c is the characteristic synchrotron frequency).

From Eq. 8 follows that the spectrum of synchrotron radiation depends only on the product $E_0 B^{1/2}$. Numerical calculations using the accurate expression for synchrotron radiation generally confirm that approximation in the form of Eq.(7) holds at least until $E \sim 10 E_m$ (Reynolds 1998).

In Fig. 2. we show 3 spectra of synchrotron radiation calculated for the same product

$$\Pi = E B^{1/2} = 61.5 \text{ TeV } \mu\text{G}^{1/2}, \quad (9)$$

but for 3 different combinations of E_0 and B : (1) $B = 3 \mu\text{G}$, $E_0 = 35.5 \text{ TeV}$; (2) $B = 5 \mu\text{G}$, $E_0 = 27.5 \text{ TeV}$; (3) $B = 8 \mu\text{G}$, $E_0 = 21.3 \text{ TeV}$. In all calculations we use the same normalization to the radio fluxes. Therefore different magnetic fields require different total energy in relativistic electrons. At the same time, because the target photon field (2.7 K MBR) for the IC scattering is fixed, there is a strong dependence of the IC γ -ray fluxes on the magnetic field. In particular, in the case of small magnetic fields $B \leq 10 \mu\text{G}$, when the radiative cooling time

$$t_{\text{sy}} \approx 1.2 \cdot 10^4 (E/10 \text{ TeV})^{-1} (B/10 \mu\text{G})^{-2} \text{ yr} \quad (10)$$

of 10 to 100 TeV electrons responsible for the observed X-rays and TeV γ -rays exceeds the age of the source, we have $F_\gamma \propto B^{-(\alpha_r+1)}$. Note that for $B \leq 3 \mu\text{G}$ the radiative losses on 2.7 K MBR become dominant.

Fig. 2 shows that the interpretation of the observed TeV radiation by IC mechanism in the framework of a simplified spatially homogeneous (one-zone) model is possible only for an ambient magnetic field in a very narrow range around $5 \mu\text{G}$. Magnetic fields $\geq 7 \mu\text{G}$ result in a strong reduction of the IC flux, while the assumption of low magnetic fields, $B \leq 4 \mu\text{G}$, leads to overproduction of γ -rays.

For such small magnetic fields a question arises whether the acceleration of electrons could be efficient enough in order to boost particles up to energies $E_0 = \Pi/B^{1/2} \sim 25 - 30 \text{ TeV}$ during the time of acceleration t_0 limited by the age 10^3 yr of SN 1006. Indeed, in the model of diffusive shock acceleration the characteristic maximum energy E_0 that a particle could achieve during the time t_0 is determined (see e.g. Lagage and Cesarsky 1983) by the shock velocity v_s , the magnetic field B , and the so-called gyrofactor η (the ratio of the particle mean free path to the gyroradius):

$$E_0 \simeq 20 \left(\frac{B}{10 \mu\text{G}} \right) \left(\frac{t_0}{10^3 \text{ yr}} \right) \times$$

² Note that our best fit value for the product $\Pi = E B^{1/2} = 61.5 \text{ TeV } \mu\text{G}^{1/2}$ is by a factor of two less than obtained by Yoshida & Yanagita 1997. The reason presumably is connected with different fluxes of X-rays used in calculations.

$$\left(\frac{v_s}{2000 \text{ km/s}}\right)^2 \eta^{-1} \text{ TeV}. \quad (11)$$

This estimate would be not significantly changed even if we take into account that in the past the shock speed was much higher than the present value v_s in Eq.(11). Indeed, even assuming that the Sedov phase in SN 1006 has started at $t_* \ll 1000$ yr and applying the Sedov solution for the shock speed in the past, $v(t) = v_s(t/t_0)^{-3/5}$ for $t \geq t_*$, the maximum energy of accelerated particles which is reached at $t \sim t_*$ could be higher than it is given by Eq.(11) only by a factor of $(t_0/t_*)^{1/5}$. Therefore, even for $t_* \sim 0.1t_0 \sim 100$ yr, the maximum energy of the particles in the past could be only by a factor of 1.5 higher than it follows from Eq.(11). On the other hand Eq.(11) does not include possible dissipative effects, such as the wave damping and the synchrotron losses of the electrons, therefore it can be considered as a good estimate for the maximum possible energy of accelerated particles.

Eqs.(9) and (11) result in a lower limit on the strength of the magnetic field

$$B \geq 12 \left(\frac{t_0}{10^3 \text{ yr}}\right)^{-2/3} \left(\frac{v_s}{2000 \text{ km/s}}\right)^{-4/3} \eta^{2/3} \mu\text{G} \quad (12)$$

The Sedov solution for the shock speed in SN 1006 gives (Willingale et al. 1996)

$$v_s \simeq 2000(d/1 \text{ kpc})^2 \text{ km/s}. \quad (13)$$

The shock speed 1400 ± 200 km/c estimated by Willingale et al. (1996) from the ROSAT X-ray data implies a rather small distance to the source, $d = 0.7 \pm 0.1$ kpc. Winkler & Long (1997) argued that the distance to the source should be larger, $d = 1.8 \pm 0.3$ kpc. At the same time, the shock speed $v_s = 2600 \pm 300$ km/c preferred by Winkler & Long (1997) is significantly lower than $\simeq 3600$ km/c following from Eq.(12) at $d = 1.8$ kpc. Given the current controversy both in the estimated shock speed and the distance, below we will discuss distances in the range from 0.7 to 1.8 kpc, but using for all distances Eq.(13).

Thus, if the shock speed does not significantly exceed 2000 km/s which implies a distance $\simeq 1$ kpc, even in the Bohm limit ($\eta = 1$) the strength of the magnetic field should not be less than $10 \mu\text{G}$ even if we assume that the effective particle acceleration has started at early stages of this SNR. This limitation could be softened by a factor of 2 for larger distances to the source (see below).

Another way to soften the conflict between the estimate of the B-field given by Eq.(12) and the value of $B \leq 7 \mu\text{G}$ needed for explanation of TeV fluxes is possible if we assume that the bulk of the observed γ -ray flux is produced outside of the shell. The highest energy electrons produced in the shell can effectively escape the acceleration region. This will give rise to an enhanced IC emission outside of the rim, namely in the interior regions of the remnant where the magnetic field could be as low

as the typical interstellar B-field. Such a leakage of electrons from the rim is unavoidable because of diffusive and convective propagation of particles. This effect should be taken into account not only for correct derivation of the electron spectrum inside the rim, but also for calculations of the IC radiation outside of the rim. Below we show that in fact the contribution of this component (missed in previous studies) is comparable or even can exceed TeV flux produced in the rim.

3.2. Inverse Compton TeV emission outside of the rim

The radio and X-ray images of SN 1006 indicate that the most probable site of particle acceleration is the thin shell of the remnant, in particular the NE rim. The width Δr of the NE rim in X-rays as measured by ROSAT does not exceed 20% of the angular radius of the remnant of about 17 arcminutes (Willingale et al. 1996) which corresponds to $r_s = 4.9 d_{\text{kpc}} \text{ pc}$ at a distance to the source $d = 1 d_{\text{kpc}} \text{ kpc}$. In calculations we assume a constant $\Delta r/r_s = 0.2$ ratio throughout the evolution of the remnant.

Due to two principal mechanisms of propagation – diffusion and convection – the relativistic particles cannot be completely confined in the rim. The characteristic escape time is $\tau_{\text{esc}} = (\tau_{\text{con}}^{-1} + \tau_{\text{dif}}^{-1})^{-1}$. The convective escape time is

$$\tau_{\text{con}}(t) = \Delta r/u_2, \quad (14)$$

where u_2 is the fluid speed downstream of the shock (in it's rest frame), thus at present $u_2 = v_s/\rho \sim 500$ km/s for the compression ratio $\rho \sim 4$. The width of the shell $\Delta r \simeq 0.2r_s \propto t^{2/5}$ assuming a Sedov-type solution for the shock radius r_s . Note that strictly speaking this solution is valid only at stages after the onset of the Sedov phase, i.e. for $t_* \leq t \leq t_0$. However the energy distribution of electrons formed in the shell at present should be dominated by particles accelerated recently, $t \geq 0.3t_0$ or so, unless one would assume that most of particles have been injected at very early stages. Therefore possible deviation of $\Delta r(t)$ from the law $\propto t^{2/5}$ at times $t \ll t_0$ does not significantly affect the spectrum of electrons at present.

The diffusive escape time is

$$\tau_{\text{dif}}(t) \simeq \frac{(\Delta r)^2}{2D(E)}, \quad (15)$$

where $D(E)$ is the diffusion coefficient in the shocked region (the rim). In the theory of shock acceleration the diffusion coefficient is generally taken in the form

$$D(E) = \eta \frac{r_g c}{3}, \quad (16)$$

where $r_g = 3.3 \cdot 10^{15} (E/10 \text{ TeV})(B/10 \mu\text{G})^{-1} \text{ cm}$ is the particle gyroradius, and $\eta \geq 1$ is the gyrofactor. The maximum confinement (and therefore the maximum energy) of particles is achieved in the Bohm diffusion regime corresponding to $\eta = 1$.

The kinetic equation for energy distribution of relativistic electrons $N(E)$ in a source reads (see e.g. Ginzburg & Syrovatskii 1964):

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E_e} [P N] - \frac{N}{\tau_{\text{esc}}} + Q, \quad (17)$$

where $Q \equiv Q(E_e, t)$ is the electron injection rate, and $P = -dE_e/dt$ is the electron energy loss rate. The solution to this equation, including the *time* and *energy* dependent escape losses is (Atoyan & Aharonian 1999):

$$N(E_e, t) = \frac{1}{P(E_e)} \int_{-\infty}^t P(\zeta_t) Q(\zeta_t, t_1) \times \exp\left(-\int_{t_1}^t \frac{dx}{\tau_{\text{esc}}(\zeta_x, x)}\right) dt_1. \quad (18)$$

The variable ζ_t corresponds to the initial energy of an electron at instant t_1 which is cooled down to given energy E_e by the instant t , and is determined from the equation

$$t - t_1 = \int_{E_e}^{\zeta_t} \frac{dE}{P(E)}. \quad (19)$$

In this paper we consider only overall (i.e. integrated over the volumes) fluxes from the NE rim (zone 1) and outside (zone 2). The electron distribution in the rim $N_1(E_e, t)$ is found assuming injection of electrons at a constant rate during the age of SN 1006, with the spectrum $Q_1(E_e)$ in the form of Eq.(1). Although the injection rate of accelerated electrons is actually time-dependent, the main contribution to the total amount of particles in the rim comes from the acceleration at epochs from $t \sim t_*$ to several times t_* (t_* corresponding to the onset of the Sedov phase) when the injection rate $Q_1(t)$ is almost time-independent (see Berezhko & Völk 1997). Since SN 1006 most probably has already reached the Sedov phase (Völk 1997) an assumption of time-independent $Q_1(E, t)$ is an adequate approximation (see below). At the same time we assume time-dependent escape, as described above (see Eq. 14 and 15), which have a stronger impact on the results than the weak time dependence of the injection rate.

Outside the rim the energy distribution $N_2(E_e, t)$ is found from the same Eq.(18) where the injection function is given by the rate of escape of electrons from the rim, $Q_2(E_e, t) = N_1/\tau_{\text{esc}}$. The region outside of the rim corresponds to the interior of the remnant close to NE rim. Therefore in this region we ignore the losses due to escape.

In Fig. 3 we show the synchrotron and IC fluxes from the NE rim and from the inner part of the remnant for the magnetic field in the rim $B_1 = 8 \mu\text{G}$ and $B_2 = 3 \mu\text{G}$ in the remnant. In order to show the impact of diffusive escape on the resulting radiation spectra, we considered 2 values for the parameter η . The case of maximum confinement of particles in the rim, $\eta = 1$, is shown by solid lines, while the dashed lines correspond to the case of $\eta = 10$. The

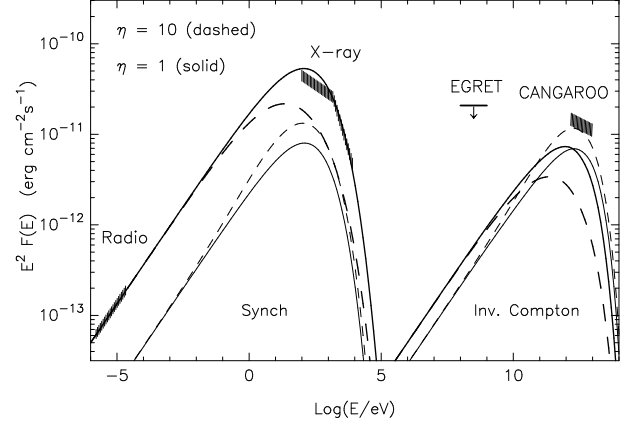


Fig. 3. The synchrotron and IC fluxes produced inside (heavy lines) and outside (thin lines) of the rim calculated within 2-zone model for two values of the gyrofactor: $\eta = 1$ (solid), and 10 (dashed). The magnetic fields inside and outside of the rim are taken as $B_1 = 8 \mu\text{G}$ and $B_2 = 3 \mu\text{G}$, respectively. The distance to the source is assumed 1 kpc.

heavy and thin lines correspond to the emission produced inside and outside of the rim, respectively.

For the parameters described above the observed X-ray spectrum of the rim is best explained for the exponential cutoff energy $E_0 = 30 \text{ TeV}$. The increase in the value of E_0 compared with the best-fit value of 21.3 TeV used in Fig. 2 for the same magnetic field $8 \mu\text{G}$ in the simple single-zone approach, is explained by diffusive escape of the electrons from the rim. For the magnetic field used, even in the Bohm limit the diffusive escape time of electrons at present is $\tau_{\text{dif}} \simeq 3500 \text{ yr}/(E/10 \text{ TeV})$, therefore for electrons with energy $E \sim (30 - 100) \text{ TeV}$ which are responsible for the X-ray fluxes, the diffusive escape time becomes comparable or even less than the age of the source. This results in a modification (steepening) of the spectral shape at high energies. In order to compensate this effect, a higher E_0 is to be assumed. Note that the convective escape time at present, $\tau_{\text{con}} = 2000 \text{ yr}$, is also comparable with the age of the source. However the convective escape does not modify the energy spectrum of electrons. This is true, to some extent, also for radiative losses in the case of small magnetic fields $B \sim 10 \mu\text{G}$, since the synchrotron cooling time then equals the source age only at $E_e \geq 100 \text{ TeV}$.

The electron escape from the rim leads to nonthermal X-ray production in a broader region (zone 2). Note that for the case of diffusion in Bohm limit ($\eta = 1$) and the assumed magnetic field $B_2 = 3 \mu\text{G}$, the X-ray flux outside of the NE rim makes $\simeq 10\%$ of the flux produced in the rim. This implies that the magnetic field B_2 cannot be larger than $5 \mu\text{G}$, otherwise the ratio of the fluxes produced outside and inside of the rim would exceed the value of about 1/3 as observed by ASCA (Koyama et al. 1995) and ROSAT (Willingale et al. 1996).

While the synchrotron radiation outside of the rim can be suppressed assuming low magnetic field B_2 , the formation of an extended IC radiation is unavoidable due to the uniform distribution of the principal target photon field for the Compton scattering - 2.7 K MBR. In particular even for $\eta = 1$ the contribution of γ -ray fluxes at ≥ 1 TeV from the region outside of the rim becomes comparable with the flux from the rim. In the case of fast diffusion corresponding to $\eta = 10$, the contribution from the extended region outside of the rim, i.e. inside the remnant at $r \leq 0.8r_s$, well dominates the overall TeV flux of SN 1006 (see Fig. 3).

The value of $E_0 = 30$ TeV in Fig. 3 is by a factor 1.5 larger than the estimate of the characteristic maximum energy of electrons following from Eq. (11) for the shock speed 2000 km/s corresponding to a distance to the source $d = 1$ kpc (see Eq. 13). This conflict could be overcome assuming a higher speed of the shock, i.e. larger d . It is important to note that the assumed distance to the source has a significant impact also on the timescale of the diffusive (but not the convective) escape of the electrons from the shell as $\tau_{\text{dif}} \propto \Delta r^2 \propto d^2$ (see Eq. 15). Therefore the relative contribution of the TeV emission produced in the interior of the remnant depends on the assumed distance to the source. This effect is seen in Fig. 4 where we show the results of calculations for two different distances currently discussed in the literature, $d = 0.7$ kpc (Willingale et al. 1996) and $d = 1.8$ kpc (Winkler & Long 1997). For the distance $d = 0.7$ kpc we used $E_0 = 18$ TeV which is 2 times larger than it follows from the estimate of the maximum energy by Eq. (11). However, even under such an extreme assumption the calculated synchrotron fluxes roll over too early, failing to reach the observed X-ray fluxes. Meanwhile for the distance $d = 1.8$ kpc the chosen value of $E_0 = 35$ TeV is in agreement with Eq (11) even for $\eta = 2$. We note that the contribution of the TeV flux produced outside of the rim is still very significant even for this large distance.

The existence of the external IC component due to the escape of electrons from the rim results in a significant increase of the overall TeV radiation, and thus allows a larger magnetic field as compared with the value $B_1 = 5 \pm 1 \mu\text{G}$ derived within the one-zone model (Section 3.1). In order to investigate the impact of this effect we have calculated the synchrotron and IC fluxes for two different combinations of B_1 and η shown in In Fig. 5. In both cases we assume for the distance to the source $d = 1.8$ kpc. The maximum electron energy $E_0 = 32$ TeV is calculated from Eq.(11). We also assume low magnetic field outside of the rim, $B_2 = B_1/4$, in order to avoid overproduction of X-radiation in this region.

The combination $B_{\text{rim}} \equiv B_1 = 5 \mu\text{G}$, $\eta = 1$ provides a good fit to the X-ray data, but it leads to an overproduction of the total TeV emission compared with the CANGAROO measurements by a factor of two. Given a possibility that the TeV emission from extended region

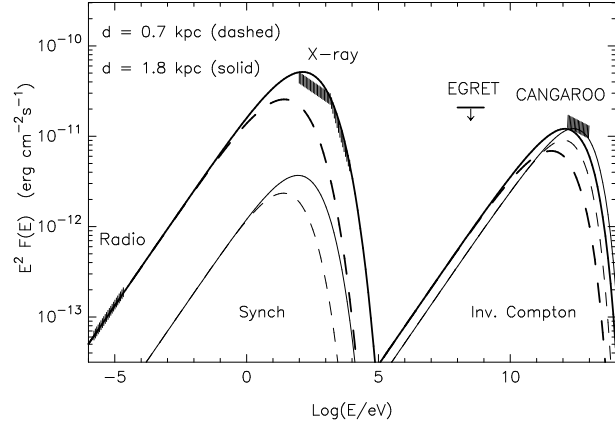


Fig. 4. The synchrotron and IC fluxes produced inside (heavy lines) and outside (thin lines) of the rim calculated within 2-zone model for two distances to the source: $d = 1.8$ kpc, and $d = 0.7$ kpc. The gyrofactor and maximum energy are: $\eta = 2$ and $E_0 = 35$ TeV for $d = 1.8$ kpc (solid lines), and $\eta = 1$ and $E_0 = 18$ TeV for $d = 0.7$ kpc (dashed lines). The magnetic fields inside and outside of the rim are taken as $B_1 = 6 \mu\text{G}$ and $B_2 = 1.5 \mu\text{G}$, respectively.

of the remnant (outside of the rim), which contributes half of the total flux, could be difficult to extract by the CANGAROO, this combination of parameters seems still acceptable. The assumption of $B_1 = 10 \mu\text{G}$ and $\eta = 2$ results in overproduction of X-rays by 50%. At the same time the predicted fluxes of TeV γ -rays from the rim are below the reported fluxes by a factor of 3.

From Fig. 5 we may draw a conclusion that the magnetic field in the rim should be within the limits $5 \leq B_1 \leq 10 \mu\text{G}$ (preferably $B_1 \simeq 6 - 8 \mu\text{G}$), and η close to 1, e.g. the diffusion in the rim should take place essentially in the Bohm limit. In order to provide maximum electron energy E_0 of order of 30 TeV, the shock speed should exceed 3000 km/s which implies a large distance to the source, $d \geq 1.5$ kpc. For this set of parameters, approximately half of the total TeV emission is contributed from the inner parts of the remnant, $r \leq 0.8r_s$. The narrow range of the required magnetic field in the rim allows rather accurate estimate of the total energy of relativistic electrons in SN 1006. For example for the distance $d = 1.8$ kpc in Fig. 4 the total electron energy in the rim is $W_e \simeq 2.9 \times 10^{48}$ erg, whereas the energy in the electrons escaped the rim is $W_e \simeq 1.9 \times 10^{48}$ erg. It should be noted that the spectrum of electrons outside of the rim is enriched by multi-TeV particles due to the effect of energy dependent ($\propto E$) diffusive escape. The total energy in electrons required to explain the X-ray and TeV γ -ray fluxes is about 5×10^{48} erg. Since the total energy of electrons depends on the B-field as $W_e \propto B^{-(1+\alpha_r)}$ the total electron energy could be reduced only by a factor of $(8/6)^{1.6} \simeq 1.6$ for the magnetic field $B = 8 \mu\text{G}$. Therefore the inverse Compton origin of

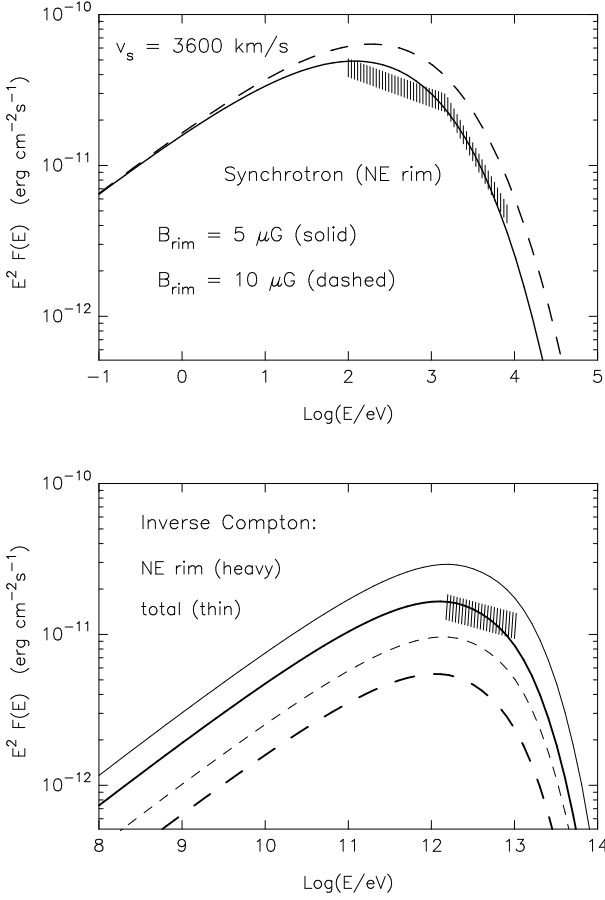


Fig. 5. The synchrotron (top panel) and IC γ -ray (bottom panel) fluxes calculated in the framework of 2-zone model for two values of the magnetic field in the rim: $B_1 = 5 \mu\text{G}$ (solid lines) and $B_1 = 10 \mu\text{G}$ (dashed lines). The magnetic field outside of the rim is taken as $B_2 = B_1/4$. The heavy lines show the fluxes from the NE rim, and thin lines correspond to the total fluxes. The distance to the source is assumed 1.8 kpc. The maximum electron energy E_0 is calculated from Eq. (11) for the gyrofactor $\eta = 1$ for $B_1 = 5 \mu\text{G}$, and $\eta = 2$ for $B_1 = 10 \mu\text{G}$.

the detected TeV radiation requires about 1 percent of the total explosion energy of SN 1006 in relativistic electrons.

The total energy of the magnetic field in the remnant with $B_2 = B_1/4 \simeq 2 \mu\text{G}$ for the distance 1.8 kpc is about 10^{46} erg. A similar amount of magnetic field energy is expected also in the rim since the amplification of the B-field there is compensated by a smaller volume of the rim. Thus, the inverse Compton origin of TeV γ -radiation implies that the conditions in SN 1006 are far from the equipartition between relativistic electrons and the magnetic field.

In all calculations above we have assumed a stationary injection rate of relativistic electrons which is a good approximation as far as the source is in an early Sedov phase. In order to demonstrate that, in Fig. 6 we show the spectra of synchrotron and IC fluxes calculated for

two different assumptions: (i) a time-independent injection rate $Q(t) = \text{const}$, (ii) injection rate in the form $Q(t) \propto (1+t/t_*)^{-1}$ with a characteristic time (onset of the Sedov phase) $t_* = 100$ yr. In both cases we have assumed acceleration spectrum given by Eq. (1) with $E_0 = 30$ TeV. For the assumed magnetic field in the rim $B_1 = 7 \mu\text{G}$ and the current shock speed $v_s = 3600$ km/s this value of E_0 implies a gyrofactor $\eta = 1.5$ (see Eq. 11). As it is seen from Fig. 6 the higher injection rate in the past does not affect significantly the fluxes of nonthermal radiation even for a very small values of $t_* = 100$ yr. The main difference between the stationary and the time-dependent injection cases is reduced to somewhat higher IC γ -ray fluxes outside of the rim. For more realistic values of $t_* \geq 300$ yr the effect of time-dependent injection becomes practically negligible.

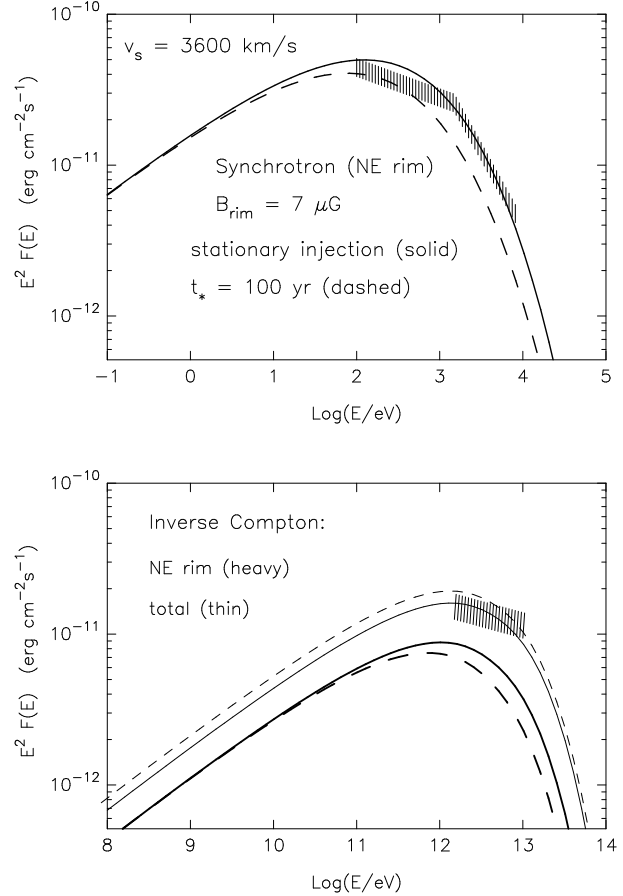


Fig. 6. The synchrotron (top panel) and IC γ -ray (bottom panel) fluxes calculated in the framework of 2-zone model for two assumptions about the injection rate of electrons: $Q(t) = \text{const}$ (solid lines), and $Q(t) \propto (1+t/t_*)^{-1}$ with $t_* = 100$ yr. In both cases $B = 7 \mu\text{G}$ and $E_0 = 30$ TeV. The distance to the source is 1.8 kpc.

The above calculations show that the electronic origin of the observed TeV γ -ray emission meets difficulties for

small distances to the source, $d \simeq 1$ kpc or less, since the latter implies a small shock speed, and therefore insufficient acceleration rate in order to accelerate electrons to energies of about 30 TeV and beyond. In case of confirmation of the recent claims about small distance to the source (Willingale et al. 1996), a possible solution to this difficulty could be an assumption of a more effective acceleration mechanism compared with the conventional diffusive shock acceleration, e.g. by invoking the mechanism of perpendicular diffusion proposed by Jokipii 1987. Another principal possibility to increase the accelerate rate is connected with an assumption of a large magnetic field in the rim, $B_1 \gg 10 \mu\text{G}$. Obviously in this scenario the TeV radiation principally cannot be explained by the IC mechanism. The only reasonable alternative could be the nucleonic origin of TeV radiation.

4. TeV gamma rays of nucleonic origin

Currently, the nucleonic origin of the observed TeV emission is treated by the community as an inadequate alternative to the IC mechanism, the main argument being the low ambient density of the gas in SN 1006, $n \simeq 0.4 \text{ cm}^{-3}$ (Willingale et al. 1996) as well as the supposed large distance to the source of about 2 kpc (Winkler and Long 1997). However these arguments are not sufficiently robust in order to dismiss such an important possibility with far going conclusions concerning the origin of the nucleonic component of galactic cosmic rays (Aharonian 1999).

Indeed, the very fact of the existence of $\gg 10$ TeV electrons as it follows from the X-ray data is an evidence for a strong shock in SN 1006, and implies a large compression factor, $\rho \simeq 4$ or even more, up to 10, as it follows from non-linear studies of shock acceleration in SNRs (Malkov 1997, Berezhko 1996, Berezhko & Völk 1997, Völk 1997, Baring et al. 1999). Therefore it is not unrealistic if one assumes a significantly higher density of the gas in the rim region, e.g. $n \simeq 2 \text{ cm}^{-3}$. The current estimates of the distance to the source also contain large uncertainties, and do not exclude a distance of about 1 kpc or even less. In particular, one of the recent studies of SN 1006 based on the ROSAT observations suggests a distance $d = 0.7 \pm 0.1$ kpc (Willingale et al. 1996). To explain the observed flux of TeV emission, for $\Gamma_p = 2$ the scaling factor $A \simeq 0.83$ is needed (Fig. 7). This requires for the total energy in accelerated protons

$$W_p \simeq 4 \times 10^{49} (n/2 \text{ cm}^{-3})^{-1} d_{\text{kpc}}^2 \text{ erg}. \quad (20)$$

This is only ~ 10 per cent of the total kinetic energy of explosion estimated for SN 1006 as 5×10^{50} erg. The numerical calculations within the kinetic theory of shock acceleration show (Berezhko 1999) that even for a large distance to SN 1006, the energy budget in accelerated protons can be sufficient to explain the TeV γ -ray emission from SN 1006 by hadronic interactions.

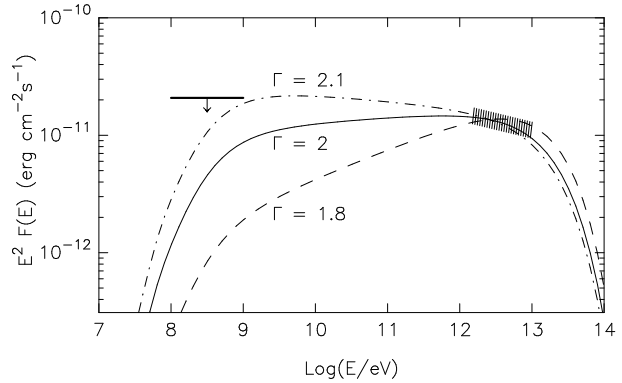


Fig. 7. The fluxes of π^0 -decay γ -rays calculated for the proton spectrum in Eq.(1) with $E = 200$ TeV, and 3 different power-law indices: $\Gamma_p = 1.8$ (dashed), 2 (solid), and 2.1 (dot-dashed). The fluxes are normalized to the observed flux at 3 TeV. This results in the values of scaling parameter $A = 0.44, 0.83$, and 1.35 , respectively.

In fact this estimate of the scaling factor A derived from the comparison of calculated and observed TeV fluxes depends significantly on the spectrum of protons. In Fig. 7 we show the π^0 -decay γ -ray fluxes calculated for 3 spectra of protons taken in the form of Eq. (1) with spectral index $\Gamma_p = 1.8, 2$, and 2.1 . The fluxes are normalized to the observed flux at 3 TeV. The corresponding values of the scaling factor are $A=0.44, 0.83$, and 1.35 , respectively. Even in the case of relatively soft spectrum of protons with $\Gamma_p = 2.1$, the required scaling factor is still acceptable taking into account that more than 20% of the energy of the supernova explosion can be transformed into accelerated protons (Berezhko & Völk 1997). Steeper spectra of protons with a slope $\Gamma_p \geq 2.1$ do not match the energy budget of the source. Such spectra are excluded also by the EGRET flux upper limit, $F_\gamma \leq 1.7 \cdot 10^{-7} \text{ ph/cm}^2\text{s}$ at $E \geq 100$ MeV (Mori 1997).

The γ -ray spectra shown in Fig. 7 are calculated assuming for the maximum energy of protons $E_0 = 200$ TeV. Although the exact value of E_0 do not noticeably change the requirements to the scaling factor A , it has a noticeable impact on the spectral form of γ -rays above 10 TeV. Therefore only future precise spectroscopic measurements in this energy region could provide an important information about E_0 . At the same time the existing sub-10 TeV data already tell us that within the framework of nucleonic model of TeV radiation of SN 1006 the cutoff energy E_0 could not be significantly less than 100 TeV.

Although in this paper we do not attempt to discuss the aspects related to the theory of diffusive shock acceleration in SNRs, it is clear that such large values of E_0 could be achieved only under the assumption of a large magnetic field in the shock region, $B \sim 10^{-4} \text{ G}$ or even more (see Eq. 11). Obviously this assumption does not leave any chance for the IC mechanism to give a noticeable contribution into the observed TeV emission. On the

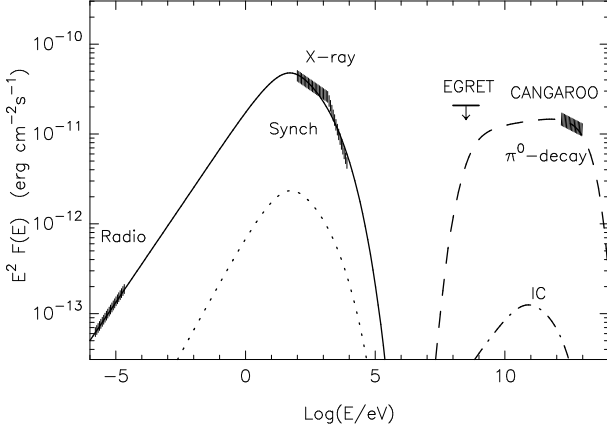


Fig. 8. The nonthermal radiation of SN 1006 calculated for large magnetic field in the NE rim $B = 70 \mu\text{G}$. Solid curves correspond to the synchrotron radiation of directly accelerated electrons, while the dotted curve corresponds to the synchrotron radiation produced by secondary (π^\pm -decay) electrons. The dashed curve shows the flux of π^0 -decay γ -rays calculated for proton spectrum with $\Gamma_p = 2$, $E_0 = 200 \text{ TeV}$, and scaling parameter $A = 0.83$. The dot-dashed line shows the flux of IC γ -rays contributed mostly by directly accelerated electrons. All fluxes shown are well dominated by the emission produced in the rim.

other hand the featureless X-ray radiation could be naturally explained by the synchrotron radiation of accelerated electrons. In such strong magnetic fields the maximum energy of accelerated electrons is determined by the balance between the acceleration rate and the synchrotron energy loss rate:

$$E_0 \simeq 45 \eta^{-1/2} \left(\frac{B}{10 \mu\text{G}} \right)^{-1/2} \left(\frac{v_s}{2000 \text{ km/s}} \right) \text{ TeV}, \quad (21)$$

and therefore, as it follows from Eq.(8) the energy of exponential cutoff in the synchrotron spectrum,

$$E_m \simeq 0.5 (v_s/2000 \text{ km/s})^2 \eta^{-1} \text{ keV}. \quad (22)$$

does not depend on neither the magnetic field nor the age of a SNR. The very fact of detection of nonthermal X-rays above 1 keV testifies that the particle acceleration takes place in the limit of Bohm diffusion ($\eta \sim 1$).

Therefore an observation of flat X-ray spectrum in the region 1-10 keV from any SNR would imply, for a reasonable shock speed in the Sedov phase $v_s \leq 4000 \text{ km/s}$, a more effective acceleration than it follows from the prediction of conventional parallel shock acceleration model.

In the regime of non-negligible synchrotron losses we should expect, in addition to the exponential cutoff at E_m , another spectral feature – a spectral break (increase of the power-law index by 0.5) at the energy E_b which is determined from the condition $t_{\text{sy}} = t_0$:

$$E_b \simeq 2.9 (B/10 \mu\text{G})^{-3} (t_0/10^3 \text{ yr})^{-2} \text{ keV}. \quad (23)$$

In Fig. 8 we show the spectrum of synchrotron radiation calculated for the following parameters: $B = 70 \mu\text{G}$, $t_0 = 700 \text{ yr}$, $v_s = 2900 \text{ km/s}$, and $\eta = 1$. For these parameters the spectral break is at $E_b \simeq 0.02 \text{ keV}$, while the exponential cutoff $E_m \simeq 1 \text{ keV}$. Although there is a gap by a factor of 20 between these two characteristic photon energies, the additional gradual steepening due to the exponential cutoff in the electron spectrum becomes noticeable already at energies $E_x \geq 0.1 E_m$.

5. Conclusions

In the previous theoretical studies of the IC γ -radiation of SN 1006 a homogeneous one-zone model has been implied (Mastichiadis & de Jager 1996, Pohl 1996, Yoshida & Yanagita 1997) which assumes that all accelerated electrons are confined in the NE rim. The magnetic field in the rim derived from these studies which would not contradict the observed X-ray to TeV γ -ray flux ratio should not exceed $7 \mu\text{G}$.

Our study of the γ -ray production in SN 1006 which includes the effect of convective and diffusive escape of electrons, allows some increase of the magnetic field up to $10 \mu\text{G}$, with preferable values being in a rather narrow range between 6 and $8 \mu\text{G}$. Given the short time of particle acceleration available, $t_0 \leq t_{\text{SN1006}} \simeq 10^3 \text{ yr}$, the assumption of such a small magnetic field requires a very high shock speed in SN 1006, $v_s \geq 3000 \text{ km/s}$, in order to provide acceleration of electrons to energies $E_0 \sim 30 \text{ TeV}$ needed for explanation of X-ray and TeV observations. This implies a *large* distance to the source, $d \geq 1.5 \text{ kpc}$.

This model allows definite predictions which could be tested by future observations. A significant, if not dominant, fraction of the IC TeV emission is to be produced outside of the NE rim. Namely, a γ -ray flux comparable with the flux from NE rim, should be then expected from the extended inner region of the remnant adjacent to the rim. The size of this region depends on the character of propagation of electrons in the rim. Indeed, even in the case of diffusion of electrons in the Bohm limit in the remnant with magnetic field $B_2 \sim 2 \mu\text{G}$, the characteristic distance of penetration of electrons towards the central region of the remnant could be estimated as

$$l(E_e) \simeq \sqrt{2 D(E_e) t_0} \simeq 0.75 (E_e/10 \text{ TeV})^{1/2} \text{ pc}. \quad (24)$$

Since the IC production of TeV γ -rays (on 2.7 K MBR) with energies less than several TeV takes place in the Thompson regime, and therefore their characteristic energy scales as $E \simeq 1 (E_e/20 \text{ TeV})^2 \text{ TeV}$, the size of the emission region of TeV gamma rays should be as large as the width of the rim, and increases linearly with energy of γ -rays. Moreover, if the propagation of electrons in the remnant is much faster than in the Bohm limit ($\eta \gg 1$), the electrons could fill up practically the entire remnant. In that case the energy dependence of the size of the γ -ray emission will be significantly weakened.

Another distinctive feature of the IC origin of TeV radiation is the spectral shape of the radiation: very hard, with the photon index $\alpha_\gamma \sim 1.5$ below 1 TeV, a flat spectrum with $\alpha_\gamma \sim 2$ between 1 and 10 TeV, and very steep above 10 TeV.

The alternative to the IC interpretation is the nucleonic origin of the observed TeV radiation. This interpretation becomes energetically comfortable, which implies no more than 10^{50} erg in accelerated protons and nuclei, if we assume (i) a *small* distance to the source of about 1 kpc or less, and (ii) a significant enhancement of the gas density in the rim due to strong shock compression. This predicts a compact size of the TeV emission comparable with that of the X-ray rim. In the region below 1 TeV the spectrum of γ -rays of nucleonic origin, with a power-law index $\alpha_\gamma \simeq \Gamma \sim 2$ is expected steeper than the spectrum of IC γ -rays. However a flatter spectrum of π^0 -decay γ -rays cannot be excluded if the protons would have an acceleration spectrum as hard as $E^{-1.5}$ (see Malkov 1997).

The shape of the spectrum of π^0 -decay γ -rays above 1 TeV depends on the characteristic maximum energy of accelerated protons. Since the flux of TeV γ -rays is no more connected with the X-ray fluxes, the value of the magnetic field in the acceleration region (NE rim) could be adopted as high as $\sim 100 \mu\text{G}$. Correspondingly, the energies $E_0 \geq 100$ TeV could be achieved. On the other hand if E_0 would be significantly less than 100 TeV, one may expect a turnover in the spectrum of γ -rays above several TeV.

Thus, it is quite possible that both in the low (sub-TeV) and in the high (multi-TeV) energy regions the IC and π^0 -decay γ -rays may have similar spectra. Therefore the spatial rather than spectroscopic measurements of γ -radiation above 100 GeV with future IACT arrays could provide decisive information about the origin of very high energy radiation of SN 1006. The IC models predict significant γ -ray fluxes not only from the rim, but also from the inner parts of the remnant. Meanwhile, the π^0 -decay γ -rays trace the density profile of the gas in the production region, therefore one should expect a rather compact γ -ray source essentially coinciding with the rim.

We emphasize that both the electronic and the nucleonic models of the observed TeV radiation of SN 1006 require a very effective acceleration of particles in the regime close to the Bohm limit. Also, the both models predict a very high conversion efficiency of the total kinetic energy of the explosion available ($\sim 5 \times 10^{50}$ erg) into relativistic particles. The energy required for relativistic electrons within the framework of the IC model is predicted with a good accuracy, given the small range of allowed B-field: $W_e \simeq 5 \times 10^{48}$ erg. This is by two orders of magnitude larger than the energy contained in the magnetic field; this suggests that the conditions in SN 1006 are far from the equipartition regime.

The nucleonic model of TeV emission requires total energy in accelerated protons from 2×10^{50} erg down to

10^{49} erg, depending on the enhancement factor for the gas density in the rim, the spectral index of the accelerated protons, and the distance to the source. In particular for moderate assumption for the spectral index $\Gamma_p = 2$, and the gas compression ratio $\rho = 4$ (i.e. $n = 1.6 \text{ cm}^{-3}$), the energy in protons is estimated $\approx 5 \times 10^{49} (d/1 \text{ kpc})^2$ erg. Note that since the magnetic field in the rim for the nucleonic model could be as high as $100 \mu\text{G}$, this model predicts a situation close to the equipartition.

High magnetic fields in the rim can equally well explain the current X-ray data. The synchrotron X-radiation in this case is produced in the regime of saturated energy losses of electrons, which results in a somewhat different spectral shape of the synchrotron fluxes. In both large and small magnetic field limits, the spectrum would be best fitted in the form $F(E) \propto E^{-\alpha_x} \exp[-(E/E_*)^{-1/2}]$, where $\alpha_x \simeq 2.1$ and $\alpha_x \simeq 1.6$ for the cases of large and small magnetic fields, respectively.

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